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Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy

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Abstract:

Forests play a crucial role in the transition towards a bioeconomy by providing biomass to substitute for fossil-based materials and energy. Increasing forest harvest levels to meet the needs of the bioeconomy may conflict with biodiversity protection and ecosystem services provided by forests. Through an optimization framework, we examined trade-offs between increasing the extraction of timber resources, and the impacts on biodiversity and non-wood ecosystem services, and investigated possibilities to reconcile trade-off with changes in forest management in 17 landscapes in boreal forests. A diverse range of alternative forest management regimes were used. The alternatives varied from set aside to continuous cover forestry and a range of management options to reflect potential applications of the current management recommendations. These included adjustments to the number of thinning, the timing of final felling and the method of regeneration. Increasing forest harvest level to the maximum economically sustainable harvest had a negative effect on the habitat suitability index, bilberry yield, deadwood diversity and carbon storage. It resulted in a loss in variation among landscapes in their conservation capacity and the ability to provide ecosystem services. Multi-objective optimization results showed that combining different forest management regimes alleviated the negative effects of increasing harvest levels to biodiversity and non-wood ecosystem services. The results indicate that careful landscape level forest management planning is crucial to minimize the ecological costs of increasing harvest levels.

Keywords: Bioeconomy, Trade-off analysis, ecosystem services, optimization, forest management

Significance Statement:

A policy-policy conflict exists between the desire to increase the utilization of bio based renewable resources and the desire to protect and conserve biodiversity. We examine and evaluate the potential for these policies to be concurrently pursued. Through a case study in Finland, we highlight the possibility to increase harvesting while promoting a set of biodiversity and ecosystem service indicators. The impacts of increasing harvesting levels are shown on a selection of both biodiversity and ecosystem service indicators. Through careful landscape level forest planning, harm caused by intensifying harvests to the biodiversity and ecosystem service indicators can be mitigated.

Introduction

In order to reduce dependence on non-renewable resources, manage natural resources sustainably, mitigate and adapt to climate change, and maintain competitiveness, Europe is moving away from an economy based on use of non-renewable resources and towards a bioeconomy. Forests provide jobs, income and biomass for substituting fossil-based materials and energy, and compared with other sources of biomass forests have the advantage of a large production potential, which does not threaten food security (Ollikainen 2014; EC 2012b). Currently, the forest and wood industry together with paper and pulp industry currently cover 30% annual turnover and 22% of the employment in the EU bioeconomy (EC 2012b). The EU forest strategy and national bioeconomy strategies and policies stress the importance of development of new wood-based materials and products (Finnish Ministry of Employment and the Economy 2014; EP 2014; Skog22 2015). In addition, more forest biomass is needed in the energy transition to meet the renewable energy targets (Beurskens & Hekkenberg 2011; Szabó et al. 2011; Bentsen & Felby 2012). The total energy use of biomass is expected to double from 2005 to 2020 to cover over half of the final renewable energy consumption of 10 exajoules in 2020, and over 55% of the biomass supply is predicted to come from forest (Scarlat et al. 2015). Consequently, national bioeconomy strategies relying on wood, climate and renewable energy policies together with an increasing demand for forest-based products are drivers for an increase in forest harvest levels in Europe (Mantau et al. 2010; Frank et al. 2016).

Intensifying biomass harvests may conflict with multiple other social economic and environmental functions of forests. Forests also contribute to water quality, reduce flooding, provide recreational services and non-wood products such as game, berries and mushrooms, prevent soil erosion, foster biodiversity and mitigate climate change through carbon sequestration and storage (EC 2012a; Nabuurs et al. 2015). Previous studies have shown trade-offs between intensifying biomass harvesting and climate regulation through carbon sequestration (Schulze et al. 2012; Zanchi et al. 2010; Kallio et al. 2013; Triviño et al. 2015), collectable goods (Peura et al. 2016), deadwood and recreational attractiveness (Verkerk et al. 2014), and maintaining high levels of biodiversity (Mönkkönen et al. 2014). Therefore, bioeconomy targets aiming at intensifying biomass harvests may conflict with other policy goals, such as the EU biodiversity strategy, which pursues halting biodiversity loss by 2020. However, previous studies also indicate that careful forest management planning may reconcile these conflicts or reduce the negative impacts (Triviño et al. 2017; Repo et al. 2015), and possibly pave the way for increasing timber harvests while minimizing harm to other ecosystem services.

In boreal Europe wood and forest-based products form the basis of current and future bioeconomy (e.g. Skog22 2015; Finnish Ministry of Employment and the Economy 2014). For example, the

Finnish forestry, the bioeconomy currently represents 16% of the national economy and wood product and pulp and paper industries cover over 40% of output and 80% of the exports of the current national bioeconomy (Finnish Ministry of Employment and the Economy 2014). To boost the transition towards an increased bio-based society, Finland aims to diversify wood use and to increase forest harvesting to almost maximum sustainable harvest level from a timber extraction perspective (Finnish Ministry of Employment and the Economy 2014; Lehtonen et al. 2016). In addition to increased timber harvests, to meet the renewable energy targets agreed in the European Union (EC 2009), for example Finland is aiming to triple the use of forest harvest residues, such as tree tops, branches and stumps in energy production compared with the year 2009 (Ministry of Employment and the Economy 2010).

A recent review suggests that intensive production forestry may have substantial effects on numerous ecosystem services, and that these effects may be harmful or beneficial depending on stakeholders (Pohjanmies et al. 2017a). Therefore, bioeconomy policy impacts on alternative stakeholder groups' vary, and identifying winners and losers by evaluating the effects of bioeconomy policies on alternative ecosystem functions and services will make political decision-making more transparent. Further, this increased intensification of forest use may promote a homogenization, which may threaten biodiversity at a landscape level (Stein et al. 2014). Since the Finnish forest land area covers 14% of the EU 28 countries (Peltola 2014), the effects of intensifying biomass harvests on forest ecosystem services and species dependent on forests will have importance on the European scale. As Sweden and Norway utilize a similar form of forest management as Finland, the relevance of this study can be valid for a much greater share of European forests.

Previous studies evaluating the transition to a forest-based bioeconomy have focused on how increasing forest harvest levels impacts either the forest carbon balance, ecosystem services or biodiversity The increase in timber harvests and forest harvest residue extraction rates reduce the carbon stocks of biomass and soils reducing the carbon sink capacity of the forest (e.g.; Sievänen et al. 2014; Frank et al. 2016). A scenario analysis in Finland to the year 2045 has shown that increasing forest harvests to maximum economically sustainable harvest level reduces the forest carbon sink and this sink may become an emission source if harvests are increased to the maximum economically sustainable harvest level (Lehtonen et al. 2016). At a European level, a scenario approach has been used to evaluate the impact on a variety of ecosystem services due to a shift in policy (Verkerk et al. 2014). From a multi-objective optimization framework questions relating to evaluating the sustainability of ecosystem services (ESS) and biodiversity have been addressed through a direct approach (i.e. Diaz-Baltiero et al. 2016; Wam et al. 2016), or through zonation techniques such as TRIAD (i.e. Montigny and MacLean 2006; Carpentier et al. 2016). Recently, Heinonen et al. (2017) have conducted a scenario analysis examining the impact differing harvesting intensities will have on a selection of biodiversity indicators. However, comprehensive assessment of the effects of increasing forest harvest levels on different ecosystem services and biodiversity are still lacking. Moreover, we do not know if and how changes in forest management could minimize the possible harm resulting from increasing harvest levels to the environment.

In this study, we explore the effects of increasing forest harvest levels on biodiversity and non-timber ecosystem services. Using a comprehensive large scale dataset combined with long-term simulation of forests and multi-objective optimization tools we i) study how increasing forest harvest level affect biodiversity, non-wood products and carbon storage in boreal forests, and ii) suggest how landscape level forest planning can minimize these possible conflicts and even produce synergies. This study quantifies the effects of policies promoting increasing harvest levels on biodiversity and ecosystem services. The findings of this study can frame policy discussions on how to determine the most appropriate harvesting level and how to adapt forest management recommendations to increasing harvesting levels, taking into account a variety of environmental criteria.

Material and Methods:

To demonstrate the impact of changing the policy towards fully utilizing the maximum sustainable yield (a quantity of timber products than can be harvested continuously year after year), a regional level analysis is proposed. As forest industries require a stable source of raw materials for production purposes, changing the quantity of timber harvested will influence the ability of industry to source materials from the local region. The region under consideration was comprised of 17 watersheds in central and southern Finland. The specific boundaries of the watersheds were defined as third-level catchment areas, delineated by the Finnish Environment Institute (SYKE 2010). The watersheds were selected to represent existing variation in overall productivity (variation in soil types) and their current conservation capacity (variation in age distribution). Each watershed has a differing initial state and a different productivity potential for providing timber, ecosystem services (ESS) and biodiversity (BD) (for more detailed description of forests in the selected watersheds, see Pohjanmies et al. 2017b). The entire region is slightly over 48,770 ha and is composed of 32,276 stands (homogenous parcels of forested land). The stand level data used was obtained from the local forest authority. The analysis focuses on understanding how increasing the intensity of the harvests from 60% to 100% of the maximum sustainable yield will impact the potential of providing other ecosystem services and maintaining biodiversity. This range of harvesting intensity was selected because it encompasses the current level (<70%) (Peltola 2014) and the targeted level according to the national policy (close to 100 %).

A total of five indicators were included in this analysis: timber income, habitat suitability index combined for six indicator species, bilberry yield (V*accinium myrtillus L.*), carbon storage in woody biomass and in soil, and deadwood diversity. Income from timber is the summation of the price of the timber assortments multiplied by the quantity of the assortments. This represents the monetary value of the flow of timber from the forest. Because of even-flow constraint in our optimization problem (see below) discounting timber income is not needed. The price of the timber is based on the assortment (i.e. saw logs or pulp wood) for each tree species, and we used the average values from the recent past (Peltola 2014).

The ecosystem service indicators selected were the carbon storage and the bilberry yield. Carbon storage was evaluated as the total carbon held within the forest. For this analysis we do not consider the potential of carbon storage in the final products of the forest industry. The carbon of standing timber and deadwood was evaluated as 50% of the dry biomass. Soil carbon was evaluated using two models. For mineral soil the Yasso07 model were used (Liski et al. 2005, Tuomi et al. 2009, 2011), and peatland soils were modeled using the carbon flux models proposed by Ojanen et al. (2014). The latter provides an underestimate of the total carbon in the forest, as the initial stocks of carbon in peat soils are not included but still allows evaluating the changes in the soil carbon pool. The quantity of bilberries, an important non-timber product in boreal forests, was calculated by the forest was predicted using the model of Miina, Hotanen and Salo (2009). The bilberry models are based on empirical data, and use the site type, dominating tree species, regeneration method, altitude, stand age and stand basal area as variables.

To evaluate the biodiversity indicators, deadwood availability and a combined habitat suitability index were used. Deadwood was selected as a biodiversity indicator because in boreal Fennoscandia, 20-25% of the forest-dwelling species are dependent on deadwood resource, and species dependent on deadwood constitute 60% of the red-listed species (Siitonen 2001). Deadwood volume is rather limited in Finnish forests, with an average of 3.8 m^3/ha of deadwood in Southern Finland and 8.0 m^3/ha of deadwood in Northern Finland (Peltola 2014), which is considerably less than in natural forests where the reported average volumes range from 20 m3/ha on infertile forest types to 120 m3/ha on more productive sites (Siitonen 2001). Since the deadwood dependent species have specific requirements for deadwood quality (e.g. Tikkanen et al. 2007), in this study deadwood availability was a function of total deadwood volume multiplied by the diversity of deadwood. Diversity, scaling between 0 and 1, was calculated as the volume of deadwood in different tree species, decay stage and diameter classes by the inverse of Simpson's diversity index (Triviño et al. 2017). Thus, a stand will have high deadwood availability if it contained large total volume divided evenly across different deadwood classes.

The combined habitat suitability index was evaluated as the combination of six habitat suitability indices. The habitat suitability of Capercaillie, hazel grouse, three-toed woodpecker, lesser-spotted woodpecker, long-tailed tit and Siberian flying squirrel (Mönkkönen et al. 2014) were integrated through a multiplicative approach (Triviño et al. 2017). These species were selected to represent a wide range of habitat types as well as social and economic values including game birds, umbrella and threatened species. Species-specific habitat suitability index (HSI) varies between 0 (unsuitable habitat) and 1 (most suitable habitat) and is related to the probability of the presence of the species in the stand. We thus calculated a combined HSI for the six species as the combined probability of independent events:

$$\mathrm{HSI_c} = 1 - \prod_{i=1}^{6}(1 - HSI_i)$$

The combined HSI is related to the probability that at least one of the species is present, and returns a high value for a stand if at least one of the species has high HSI, and a value close to zero if a stand provides low suitability for all the species.

The initial forest data was provided by the Finnish Forest Center. The data is comprised of stand level forest information, with a description of the stand level characteristics and information on the strata which compose the forest stand. The stands have a median area of 0.98 ha, with a minimum area of 0.01 ha and a maximum area of 61.79 ha. The forest is inventoried through remote sensing technology (Airborne Lidar Scanning; Næsett 2007), and is updated in a 10 year cycle. Predictions of the future forest states were made through the use of a forest simulator (SIMO; Rasinmäki et al. 2009). SIMO is an adaptive simulation open-source framework designed specifically for forest management planning. The modelling framework consists of over 400 equations to predict, among other things, the growth of the diameter and height of each tree and the probability of a tree death. For the majority of the management regimes, the prediction of the development of the forest stand was conducted using the forest models of Hynynen et al. (2002). One management regime (continuous cover forestry, CCF) used the Hynynen et al. (2002) models to predict the forest stand development until the point in time where harvesting actions occurred, and converted the stand to a CCF stand. Following conversion to a CCF stand, the continued development of the forest stand was predicted using the models by Pukkala et al. (2013). This was done as the models of Hynynen et al. (2002) are specific to even-aged forests, and the models of Pukkala et al. (2013) are developed for uneven-aged forests. A time horizon of 100 years was selected, divided into 20 periods each 5 years long. The length of the time horizon was selected to examine what may happen over an entire rotation period (the length of time required for a seedling to grow into a harvestable tree). This choice was made to ensure that the harvest level could be kept constant for the continued sequence of rotation periods.

Management regimes were created to reflect potential decisions that forest owners may make over the time horizon. A total of 19 management regimes were used to represent how the forest may be managed. One management regime for all stands was to *set aside* (SA), and simply allow the stand to grow. A second alternative was to conduct *continuous cover forestry* (CCF), where periodically large trees are removed, and growth and regeneration is left to nature. The remaining alternatives were modifications of conducting *business as usual* (BAU). Starting from bare ground, the management regime starts with a selection of pre-commercial actions was taken to promote forest growth, followed by possible commercial thinnings and final felling to extract timber. Modifications were created by restricting the number of thinnings, by adjusting the timing of final felling, and by switching from artificial regeneration to natural regeneration. A more detailed description of the management regimes can be found in the supplementary material (Appendix S1).

To examine a variety of potential scenarios, we utilize a theoretical landscape level planning approach, where all decisions are taken at an individual stand level. From a conservation perspective, species persistence primarily depends upon habitat availability at the landscape/regional scale (Fahrig 2017). Thus, we focus on examining the trade-offs between harvesting actions and habitat availability of forest indicator species, i.e. areas of less intensively managed forests at a landscape scale.

Once the stands have been predicted for the feasible management regimes, optimization methods were used to evaluate the maximum possible periodic harvest. This is an even-flow problem, where each period has a similar quantity of timber flowing from the forest to the consumers. This is a common problem in forestry, as pulp and timber mills require a relatively constant flow of inputs to enable continual production. The optimization model can be framed as a linear programming problem (Johnson & Scheurmann 1997):

Model 1:

$$[1] \quad \max z = \sum_{k=1}^{K} \sum_{j=1}^{J_k} c_{kj1} x_{kj}$$

Subject to:

$$[2] \quad \sum_{k=1}^{K} \sum_{j=1}^{J_k} c_{kj1} x_{kj} \leq \sum_{k=1}^{K} \sum_{j=1}^{J_k} c_{kjt} x_{kj}, t = 2, \ldots, T$$

$$[3] \quad \sum_{j=1}^{J_k} x_{kj} = 1, k = 1, \ldots, J$$

$$[4] \quad x_{kj} \geq 0 \forall k = 1, \ldots, K, j = 1, \ldots, J_k$$

where z is the objective function value, c_{kjt} is the value of the timber available from stand k according to management regime j at the t^{th} period, x_{kj} is the decision for stand k to conduct management regime j, K is the total number of stands under consideration, J_k is the total number of management regimes for stand k, and T is the total number of periods under consideration. In this linear programming model, the objective function is to maximize the first period timber flows, while the constraint detailed in [2] ensures that all future periods can provide at least as much timber flow as what was obtained in the first period. Constraint [3] ensures that each stand is assigned some management regime and [4] is a non-negativity constraint, ensuring that the decisions for assigning management regimes are always positive (or zero).

The objective value of the previous model highlighted the maximum even-flow of the value of timber and does not actively consider the optimization of any other indicators. A second model was developed to analyze the trade-off between the even-flow requirement and a selection of four provisioning and conservation indicators. To accomplish this, a compromise programming formulation was used (Yu 1973). Compromise programming allows for selecting the most appropriate distance metric from L^p space, and relates to other multi-objective programming methods (Tamiz et al. 1998, Romero et al. 1998, Cisneros et al. 2011). When the distance metric $L^p = 1$, the focus is on minimizing the aggregated sum of the deviations, while the distance metric $L^p = \infty$ focuses on minimizing the maximum sum of the deviations. For this study, we use the distance metric $L^p = 1$, assuming equal weights for all objectives However, another metric might be equally valid depending on the preferences of the decision maker. The objective function was to minimize the weighted normalized difference from the ideal and nadir values, while ensuring that the timber provided by the plan meets a specific percentage of the theoretical maximum even-flow found in the previous model. This provided a method of evaluating the trade-offs between increasing the amount of timber harvested and the impacts on the ecosystem services.

Model 2:

$$[5] \quad \min I = \left(\sum_{e=1}^{E} {w_e}^p \left| \frac{d_e^* - y_e}{d_e^* - d_{e*}} \right|^p \right)^{1/p}$$

Subject to

$$[6] \quad \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{j=1}^{J_k} d_{ekjt}x_{kj} = y_e, \quad e \in E$$

$$[7] \quad \sum_{k=1}^{K}\sum_{j=1}^{J_k} c_{kj1}x_{kj} \geq z * f$$

and [2], [3] and [4].

where d_{ekjt} is the value of the ecosystem service or biodiversity indicator value *e* available from stand *k* according to management regime *j* at the t^{th} period, w_e is the preferential weight assigned to criterion e, while d_e^* and d_{e*} are the ideal and anti-ideal values for criterion e.[8] Parameter *f* is set to determine the percentage of maximum periodic timber harvest. The trade-off between the set of ecosystem services and biodiversity indicator values in the objective function and the timber required can be evaluated by modifying this parameter. The objective function [5] minimizes the weighted normalized distance for all criteria under consideration. As presented, this is a non-linear model, so prior to solving, a conversion to a linear format eases the computational difficulties, for specific techniques to accomplish this readers are referred to Tamiz et al. 1998. Constraint [6] calculates the ecosystem services and biodiversity values for a specific decision, and constraint [7] requires that a specific flow of timber is met for each time period. To summarize, in this model, the objective function was to maximize a set of ecosystem services and biodiversity indicators while the constraints ensure a steady flow of timber for all periods under consideration.

To find the ideal and anti-ideal values (d_e^* and d_{e*}), the following simple linear programming model was used:

$$[8] \quad \max d_e^* \; or \; \min d_{e*} = \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{j=1}^{J_k} d_{ekjt} x_{kj}$$

subject to [3] and [4].

To highlight the importance of planning for all indicators of interest, we examined the range of solutions possible if the focus was only on the requirement of sustaining an even-flow of timber resources. If the only indicator of interest is the even-flow of timber, as the requirement for maximum even-flow is decreased, additional options of achieving the specific levels of timber were possible. To evaluate the expected result of the ecosystem services and biodiversity indicators, we enumerated a large sample of possible solutions. The solutions were created with an aim to be evenly distributed amongst the possible outcomes. A detailed description of how these solutions were created can be found in the supplementary material (Appendix S2).

Results

Increasing forest harvest level to the maximum economically sustainable harvest will have a negative effect on biodiversity and non-timber ecosystem services even when management was optimized to meet alternative objectives (Figure 1). Maximizing harvest level is particularly detrimental to biodiversity indicators. If 100% of the maximum sustainable yield was harvested the deadwood availability decreased 70% and combined habitat availability by 26% compared to when focusing the sustainable yield to 60% of the maximum. Losses for ecosystem service indicators were more moderate: 30% decline in bilberry yield, and 12% in carbon storage (Figure 1). The losses in carbon storage showed a rather linear decline with increasing harvest level. For bilberry yield, the timber harvest level can increase up to some 85-90% of the maximum sustainable harvest level without substantial negative impacts. As the harvest levels increased the habitat availability and deadwood diversity indicator values of the studied 17 watersheds converge (Figure 1, grey and red lines). This suggests a loss of landscape specific biodiversity characteristics.

The results above were based on multi-objective optimization, i.e. are the highest achievable levels of biodiversity and ecosystem service indicators at different levels of timber harvesting, and achieving them requires careful planning. For this analysis, we assumed equal importance between objectives. However, this assumption may be relaxed through integration of stakeholder preferences. This can be done e.g. through interactive multiobjective optimization, where stakeholders are allowed to gain an understanding of the decision problem and provide preferences throughout the process. (Miettinen, 1999; Miettinen and Ruiz 2016). To examine the importance of setting appropriate weights, a payoff table highlighting the best and worst cases for each indicator at each harvesting level is provided in Appendix S3. As the harvesting requirement is reduced, the range of optimal solutions increases, highlighting how at the landscape level preferences (i.e. regional planners) can influence the optimal solution. If careful planning is not done considerable losses in non-timber benefits accrue in almost all cases (Figure 1, dashed blue line). Only at the maximum level of timber harvesting level, all of the solutions are rather similar, and consequently, there is very little flexibility for planning (Figure 1 & 2). Planning benefits are particularly large for deadwood availability, as there is a loss of nearly half of deadwood diversity due to timber harvesting incurred without planning at 60% level of timber-flow (Figure 2).

The distributions of the optimal stand specific management regimes are different for different harvest levels (Figure 3). At the lowest harvest levels (60% of the maximum), the management is dominated by three regimes: SA (38%), CCF (42%) and a version of BAU with green tree retention (13%). Together these three regimes account for 93% of the total area. The remaining management regimes were applied to the remaining area, however none were applied to more than 2% of the management of the entire region. The stands assigned to the SA regime consisted of a range of initial conditions. For the 60% harvest level, the SA regimes had an initial average of 188 m3/ha of timber and an average age of 59 years, compared to 149 m3/ha and 47 years for the general initial conditions. Alternatively, when the requirement for timber flow is the maximum sustainable harvest level, seven management regimes account for 91% of the total area with the continuous cover forestry (41%) being the most prominent regime. At this harvest level, the possibility to set aside the forest is limited, and the harm is minimized by a diverse set of clear-cut based management regimes with varying rotation lengths and thinning levels, as well as with a frequent use of continuous cover forestry.

Discussion

Our results show that focusing a strategy of increased timber flow will likely result in considerable losses in biodiversity and ecosystem services, and consequently produce ecological and social costs. Ecological costs are particularly pronounced as the indicators are shown to decrease >30% compared to what is achievable at the current timber harvest levels. At current harvest levels biodiversity is already threatened due to intensive forestry reducing characteristics, resources and variation that are important for forest species (Hanski 2000). Deadwood stocks in production forests of southern Finland are ~3-4 m^3/ha; for more demanding deadwood associated species to occur a level of 20 m^3/ha is required (e.g. Junninen & Komonen 2011). At current harvesting levels, the expected deadwood availability values for our study region correspond rather well to measured values. Thus, the projected 70% decrease in deadwood availability is realistic and would further shift the quality of forests away from the ecological sustainable level of deadwood resources. Therefore, pursuing the bioeconomy policy will further increase species endangerment, for forest-associated species in general and deadwood dependent species in particular.

Our results also indicate that by increasing the level of harvesting there will be a loss of variation between landscapes, which initially differed in their ability to provide non-timber ecosystem services and biodiversity. In other words, landscapes with a poor biodiversity values at current harvest levels (<70%) remain poor, while highly biodiverse landscapes also become poor. This convergence among landscapes occurs because with increasing harvest level, harvesting actions are conducted in stands with progressively higher biodiversity values. The convergence reduces environmental heterogeneity at a regional scale, which is a further threat to biodiversity. There is strong evidence that environmental heterogeneity is an important universal driver of biodiversity at landscape to global extents (Stein et al. 2014).

For this study, we did not include potential climate change impacts into the growth models, so the results may be an under/over estimation of the different ecosystem services. For instance, in Finland, increased temperatures could positively impact forest growth and tree mortality. This would simultaneously increase deadwood decomposition resulting in a faster turnover rate of deadwood resources (Mazziotta et al. 2014) and a larger proportion of deadwood associated species losing habitats than gaining more habitat (Mazziotta et al. 2016). The result would be positive from a timber extraction point of view, but negative from a biodiversity perspective supporting the findings of earlier studies (Schulze et al. 2012; Sievänen et al. 2014). Forest management changes, which increase forest carbon stocks, such as fertilization, could possibly partly compensate for the forest carbon loss. However, fertilization raises other environmental concerns. Thus, increased harvest level will have a direct negative effect but likely also an indirect negative effect, via climate change, on biodiversity.

Additionally, we did not study the impacts of other possible sources of uncertainty. The development of forest resources was predicted through the use of growth models. These models are based on sets of assumptions and as with all forecasts the future cannot be predicted without error (Diebold 2001). The possibility exists to include these sources of uncertainty in the optimization framework through stochastic programming (Birge & Louveux 2011). Through a stochastic framework, questions related to the distribution of the indicators can be examined. However, currently the computational cost to execute such a framework on this problem is exceptionally high. For the question related to the policy of implementing higher sustainable yields, uncertainties need not be explicitly included in the framework, rather the possible impacts should be discussed.

In this study, the estimate of carbon stored in the forest is an underestimate, as the initial state of carbon stored in the peat is not included in the analysis. This was due to a lack of precise data regarding the quantity of peat for the large area under consideration. In this study, a total of 15% of the area was forested peatlands, which could reflect a store of carbon of 3,600 kt C (using estimates of 500 t C/ha) (Minkkinen & Laine 1998; Turunen 2008). As this study is essentially interested in the amount of carbon sequestered (where this change can be seen through the fluxes), incorporating the initial state of stored carbon from the peat lands will not impact the results of this study.

This study focused on the use of providing a steady amount of timber resources from the forest over a long period of time. This concept has been a feature of sustainable forestry since the early 18th century (von Carlowitz 1713). This requirement to provide a continuous timber supply is an economic sustainability requirement, which prevents excessive destruction to the forests. However, while the forests may provide a constant flow of timber, various other issues of sustainability, such as sustained provision of collectable forest products, or maintenance of biodiversity, are ignored with this approach. For biodiversity, persistence in time of species is critical because global extinctions are irreversible and regional extinctions maybe time-consuming to remedy given the sparsity of source populations in production forest landscapes (Hanski 2000). Thus, sustained availability of habitats and even flow of resources for species are critical. From the bioeconomy perspective, the supply of each specific biomass type may require a sustainable flow (Ollikainen 2014), so the realm of sustainability should be opened up and include various economic and ecological aspects of sustainability.

The potential exists to increase the timber harvest level while limiting the negative impacts on ecosystem services and biodiversity indicators. In this study, this potential was evaluated through optimization, and implementation would require careful planning. Relative benefits from planning are generally high but varied among the indicators (Fig 2). Careful landscape level planning can offer a means to reduce the negative effects of increasing forest harvest levels on biodiversity and ecosystem services. In this study, a failure in implementation of optimal landscape level plans resulted in a loss of 30-40% in ecosystem service and biodiversity indicators at most timber harvesting levels (Figure 1). Thus, to limit the losses of the potential of landscapes to maintain biodiversity and ecosystem services careful planning will become increasingly important in the era of bioeconomy. How to successfully conduct this planning should be aided through an exploration of historical development of forest resources. For instance, Angelstam et al. (2018) and Naumov et al. (2018) have explored the competition of biodiversity and timber production through a spatial comparison of countries with different historical development of forest use. Ideally, resource harvesting should be targeted to sites with the highest timber production potential and cause the smallest losses to biodiversity and ecosystem services. Correspondingly, resources for nature conservation should be invested to maintaining non-timber ecosystem service provisioning in areas with high ecological and social values but low timber production potential. Kareksela et al. (2013) coined this as negative impact avoidance approach and successfully applied this to land use planning for peat mining.

But mere planning is not enough; plans need to be implemented. In a forestry context, this will require involvement of and acceptance by forest owners. If only a proportion of stakeholders ignore the suggested management plan, inefficiencies will be introduced. In practice, conducting careful landscape level planning is difficult to accomplish, as the forest properties are controlled by a large variety of stakeholders with differing intentions and objectives (Eriksson and Hammer 2006; Angelstam et al. 2011). Some commodities such as timber are considered private property, benefiting primarily the landowner while others are considered public goods. For example, climate change mitigation provides a global benefit by reducing atmospheric CO2 levels, while water quality regulation, and recreational use, natural collectable products (e.g., berries and mushrooms) profit mostly the local community. Private landowners typically lack the incentive to manage land to provide ecosystem services and biodiversity conservation benefits in cases where the benefits produced on their land accrue to others.

However, aggregating forest planning for even a small set of forest holdings can mitigate the trade-off between increasing forest harvest levels. For example, e.g. Pohjanmies et al. (2017b) observed that approximately 100 stands or 200 ha, i.e. less than ten owners, is large enough to effectively mitigate the conflict between timber production and carbon storage. Thus, incentivising forest owner's collaboration to landscape level planning may not be an impossible mission. Because priorities between forest owner level planning and landscape and regional level forest planning are often mismatched, the implementation of the landscape level plan incurs costs and benefits unevenly among forest owners. To align the priorities, policy tools, such as monetary compensation for voluntary conservation (e. g. METSO 2008), could compensate for losses to those forest owners who face large private costs for providing common goods in terms of biodiversity and non-timber ecosystem services. One way to differentiate landscapes where environmental and social objectives have priority from timber production landscapes in regional forest resource management planning are systematic zoning tools, such as the inverse spatial prioritization (Kareksela et al. 2013). Zoning, together with incentives and monetary compensations to forest owners for extra planning work, and economic losses could improve the protection of public interests in boreal production forests in the era of bioeconomy.

In the era of bio-economy ensuring ecological social and economic sustainably of boreal forest management requires, in addition to careful planning, diversification of management regimes. We found that at most levels of timber harvesting, optimal management is dominated by set-asides and continuous cover forestry, and clear-cut based forestry becomes the prevailing – but not exclusive – management regime only at very high levels of timber harvesting (>95%). Thus, by relying on the application of the standard practice of final felling by clear-cuts results in costs for economic, ecological and social aspects. These results are similar to earlier literature, where continuous cover forestry is shown to often be better in providing timber and non-timber ecosystem services than clear-cut forestry (Pukkala et al.2011; Pukkala 2016; Tahvonen 2016; Tahvonen & Rämö 2016; Peura et al. 2018).

Some forest certification programs (e.g, FSC) require setting aside a minimum of 5% of forest area. Our results suggest that optimal set-aside level is much higher at most levels of timber harvesting, e.g. more than 25% currently (at <70% harvest level), and 8% at 90% timber harvest level. Thus, it is optimal to concentrate forest harvesting to sites where yields are highest and losses to biodiversity and non-timber ecosystem services lowest, allowing for large areas of forests to be set aside. Currently, around 2% of forest area is formally protected in south boreal Fennoscandia, with an estimated 6-7% of the forested area protected both formally and voluntarily (Peltola 2014; Angelstam et al. 2011) and therefore, more investments in forest protection are optimal and possible even with increasing timber requirements.

Economic growth and the shift from non-renewable resources is a very understandable justification for EU and national level strategies to promote increased extraction of timber resources. However, this focus should link to other international, EU level and national level policy agreements that aim at halting biodiversity loss and maintain ecosystem services. A recent EU Parliament resolution (EU Parliament 2016) urges for considerable additional efforts for biodiversity protection in European forests. Likewise, the international Strategic Plan for Biodiversity 2011-2020 (Aichi Biodiversity Targets) requires that by 2020 all areas under forestry are managed sustainably ensuring the conservation of biodiversity, 17 per cent of terrestrial area is conserved through effectively and equitably managed, well-connected protected areas and other effective area-based conservation measures, and ecosystems that provide essential services are restored and safeguarded. Our results indicate that the Finnish forest strategy (i.e. achieving maximal sustainable timber harvest level) as well as EU level and national bioeconomy policies (targeting considerable increases in forest harvesting) are in conflict with the biodiversity and ecosystem services policies, i.e. there is a policy-policy gap. Policy analysis identifies this ignorance of goal conflicts in Finnish forest policies (Makkonen et al. 2015; Kröger & Raitio 2016). Disintegrated, sectoral policies are ineffective and unsustainable (Winkel & Sotirov 2016), and better policy coherence is therefore desirable. Our results show that to bridge the policy-policy gap in forest use in practice, a multi-objective planning approach is needed where economic objectives are neatly balanced with environmental and social values.

Conclusions

Increasing the requirement for resource extraction from natural resources will require an appropriate balance between economic, ecological and social objectives, possible with careful multi-objective planning. In boreal forests, the diversification of management regimes will be needed for overall sustainability, and a shift from clear-cut forestry would provide considerable benefits for forest owners and the society. Our results indicate that careful forest planning can reduce the negative effects of increasing forest harvest levels on biodiversity and ecosystem services.

From practical perspective, a viable solution would be landscape sparing, i.e. spatially segregating landscape where timber production is the main objective from landscape with a better balance between objectives. Even though in general the effects of fragmentation are much weaker than the effects of habitat loss on a wide range of ecological responses (Fahrig 2017) ecological research has concluded that if a limited area of species habitats can be protected they should be protected in spatially aggregated clusters rather than as randomly scattered fragments.

This will generally reduce species extinction risk and increase the conservation benefits for a given total area protected (Hanski 2011). Also from the mere human perspective it may well be reasonable to aggregate efforts because, for example, larger tracks of mature forests can be found more appealing for recreation than an equal area in small fragments.

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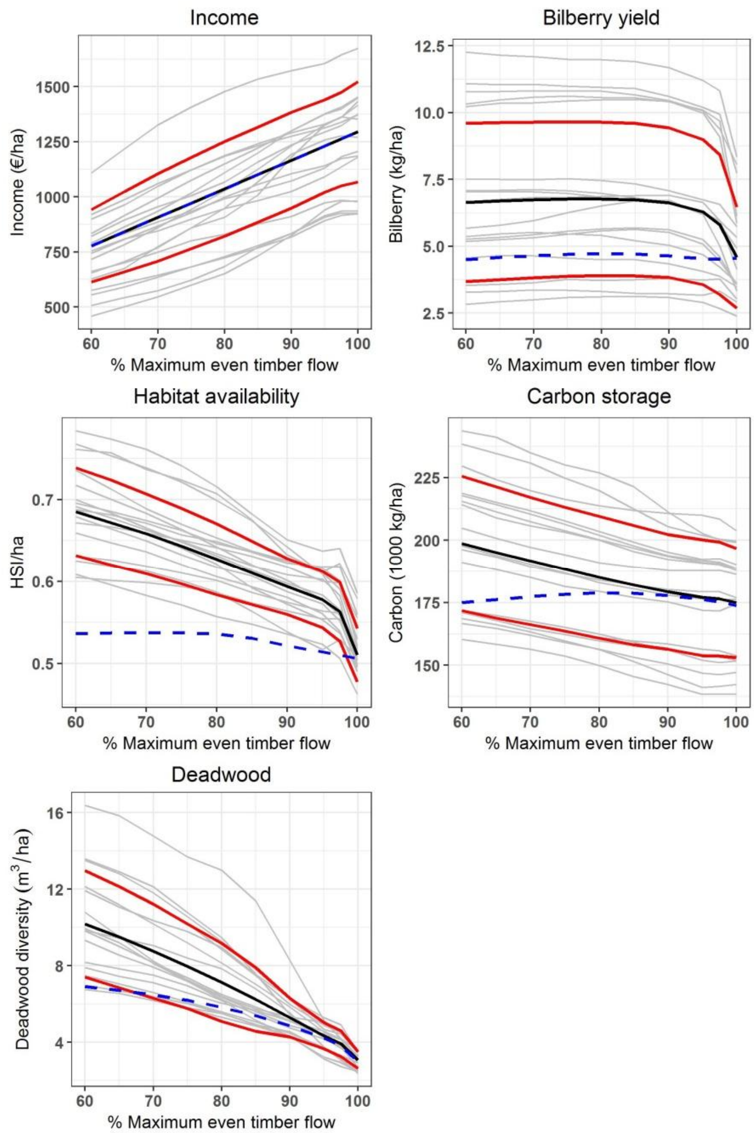

Figure 1. The combined results of all harvest levels considered. All indicators are evaluated as a per hectare. With a steady increase requirement for timber flow there is a rapid decline in the average levels of other indicators (black line). Additionally, as timber flow is increased there is convergence in values of habitat suitability and deadwood diversity between watersheds (light grey lines). This can be seen as a narrowing in the standard deviation (thick red lines). The expected solution when ecosystem services and biodiversity are not included in the optimization is shown with the dashed blue line.

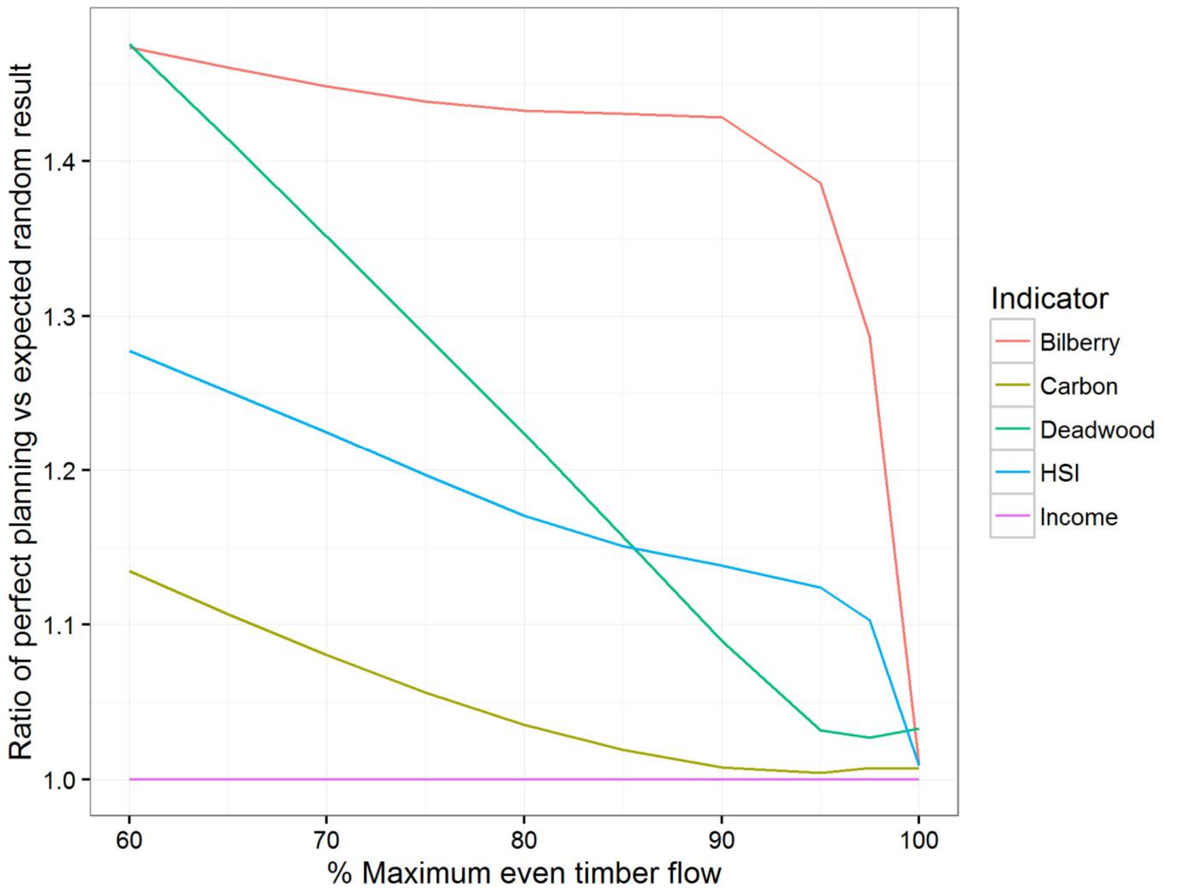

Figure 2. The benefits of ensuring proper planning at different levels of even timber-flow in terms of the ratio of the values for the optimized solution and the expected result where biodiversity indicators and ecosystem services were not included in the objective function.

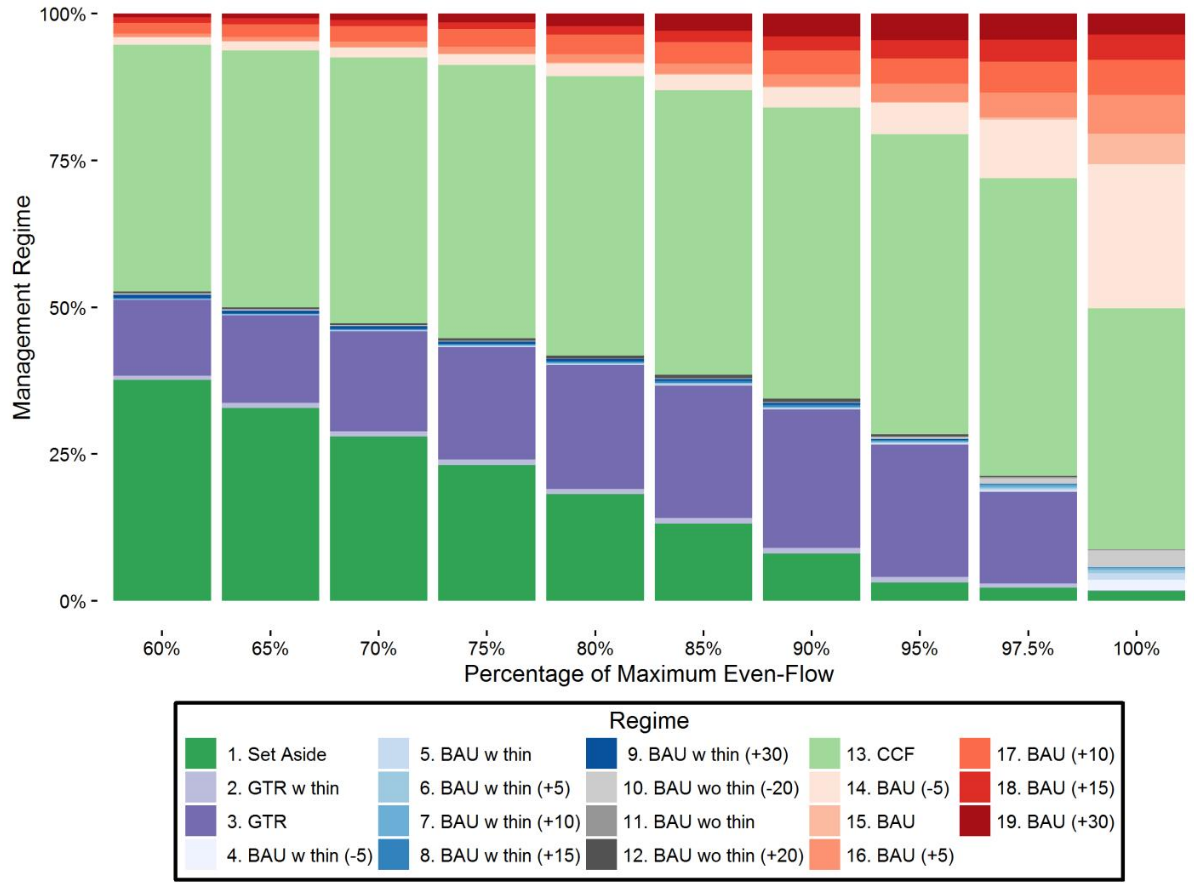

Figure 3. Change in the area managed according to the different regimes when there is an increasing requirement for even-flow of timber in the optimized solutions. BAU refers to alternative clear-cut based management regimes with variable thinning intensities and rotation lengths (GTR = green tree retention, w thin = with thinnings before clear felling, wo thin = with no thinnings). CCF refers to continuous cover forestry with not final felling by clear-cut, and set aside denotes permanent protection (no management). For description of management regimes see Appendix S1.